



Sb-Based RTDs: Advantages and Modeling Challenges

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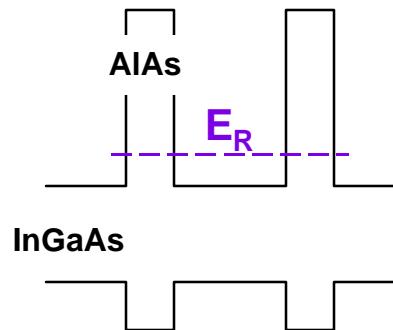
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Outline: Resonant Interband Tunneling Diodes

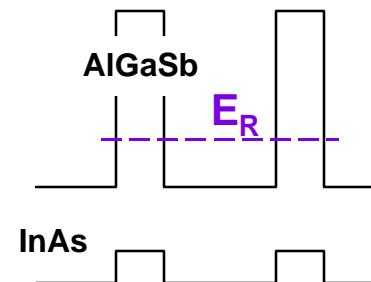
- Type I and II tunneling structure survey
- Simple model
 - Conservation of Energy, Momentum
 - Type I and II voltage level comparison
 - New Tsu-Esaki I(V) formula for Type II
- Circuit implications
- Modeling challenges
 - Light hole, heavy hole tunneling
 - Well charge accumulation
 - GaSbAs well heavy hole strain shift
 - AlSbAs barrier valence band discontinuity

Resonant tunneling structures

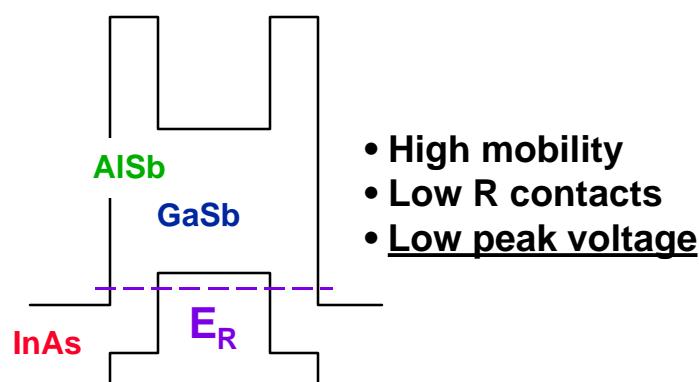
Type 1



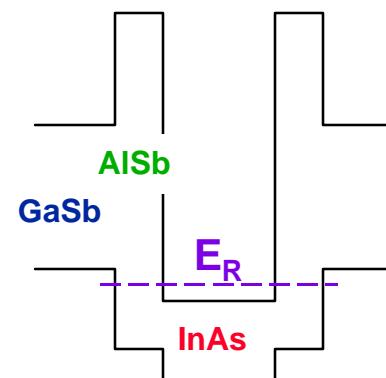
Type 1.5



Type 2A

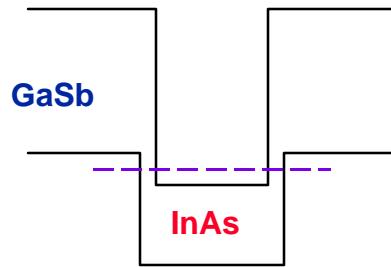


Type 2B

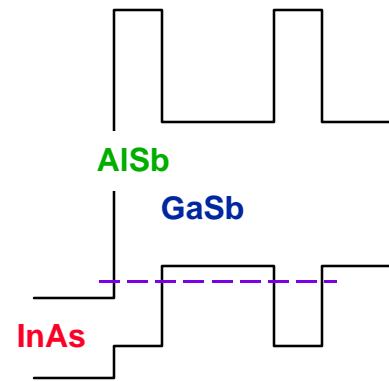
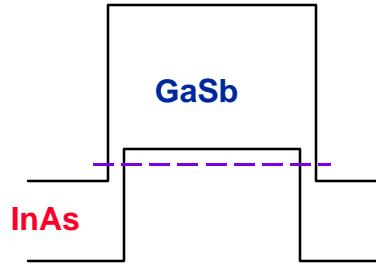
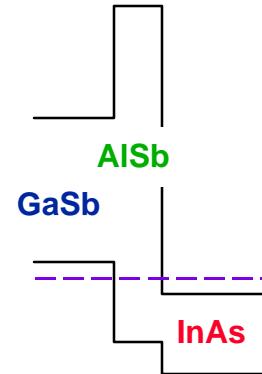


InAs/AlSb/GaSb Variations

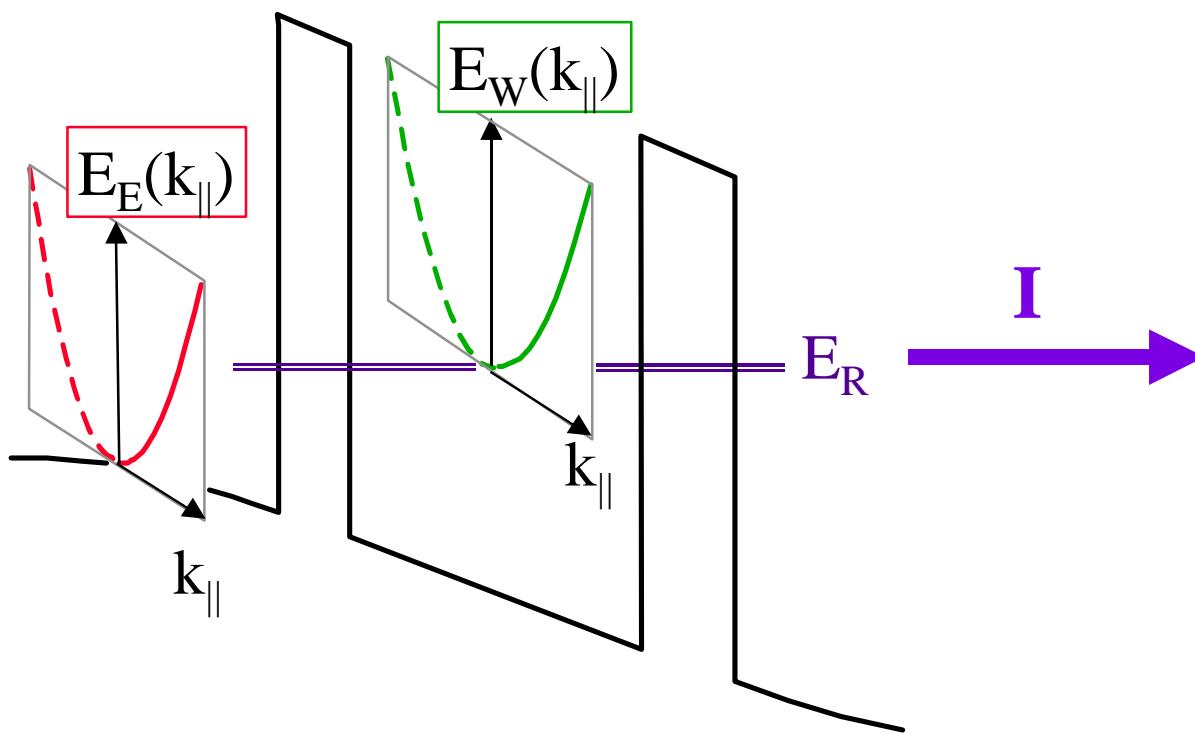
SINGLE BARRIER



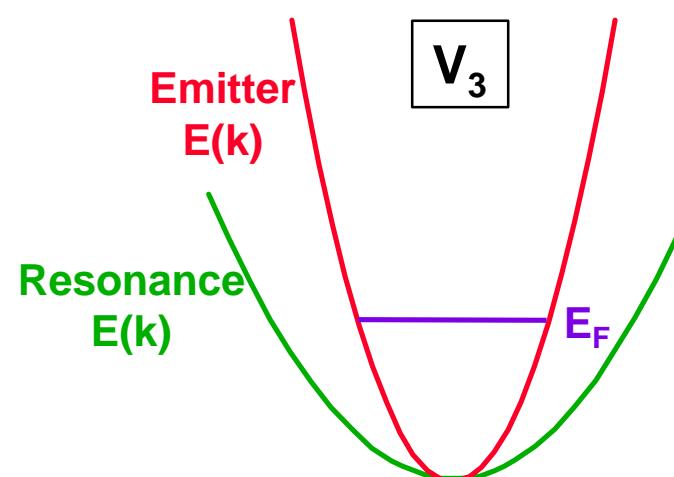
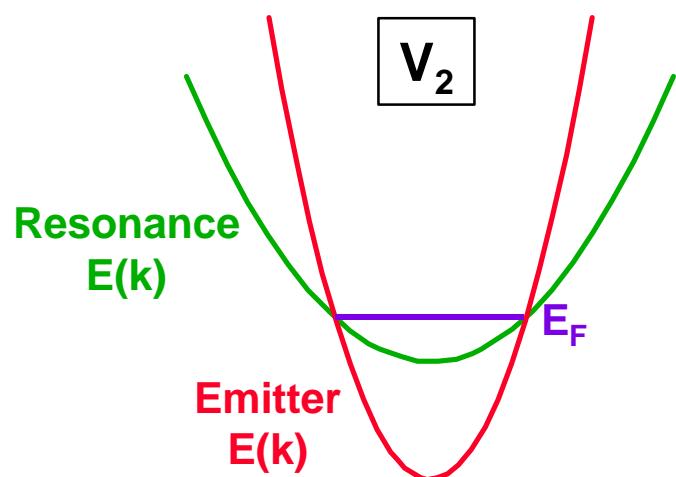
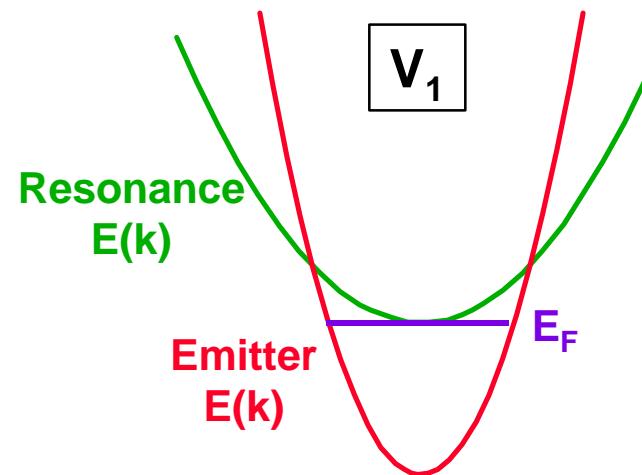
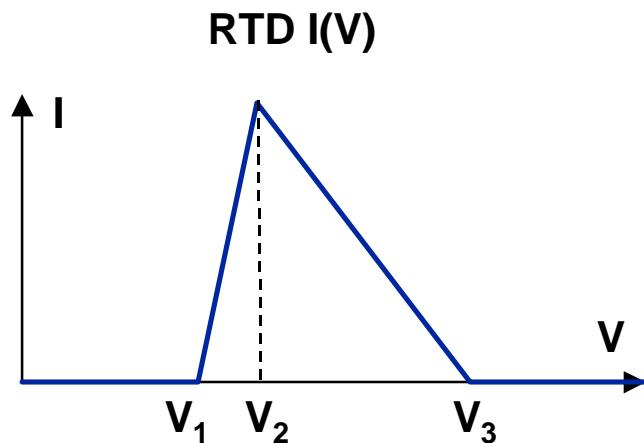
ASYMMETRIC



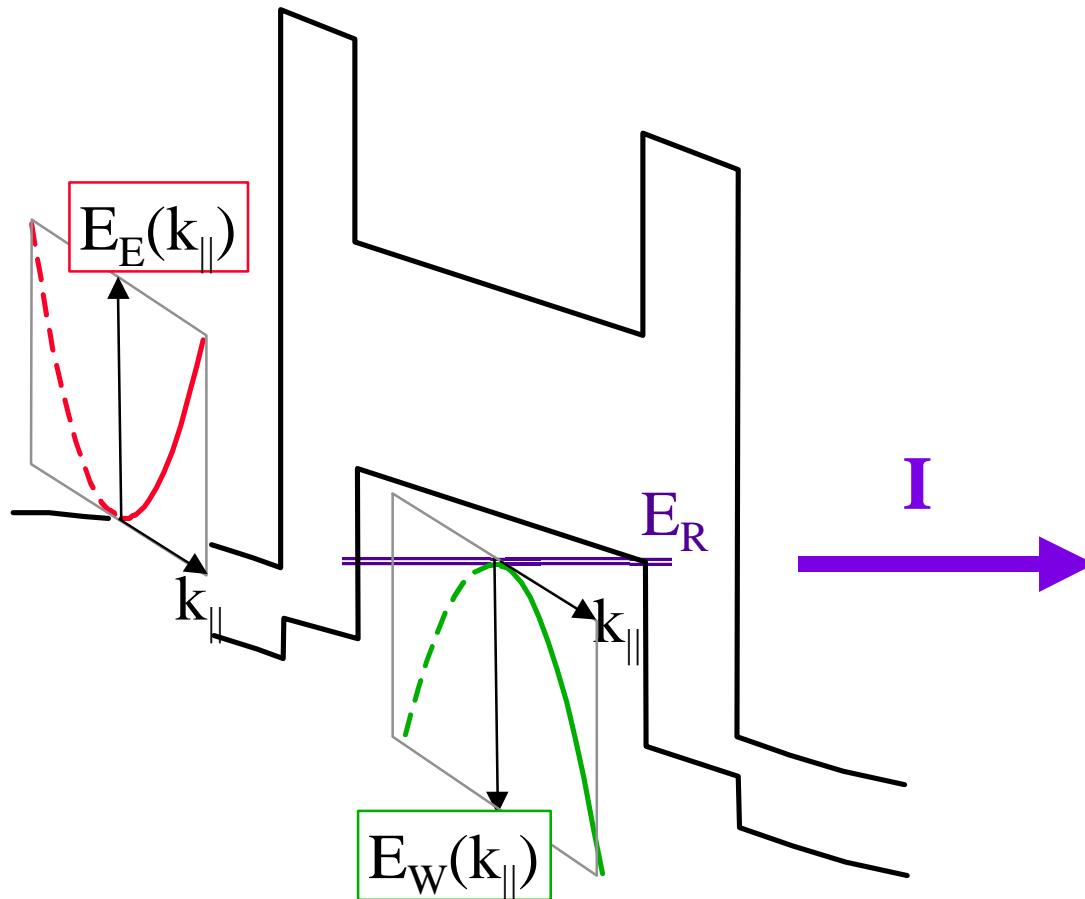
Type 1 RTD Parabolic E vs k_{\parallel}



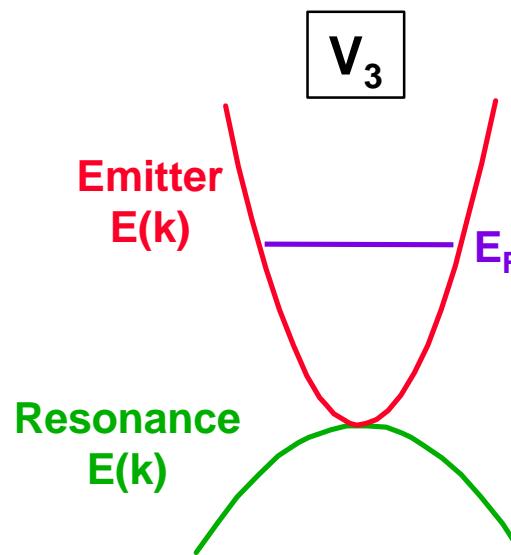
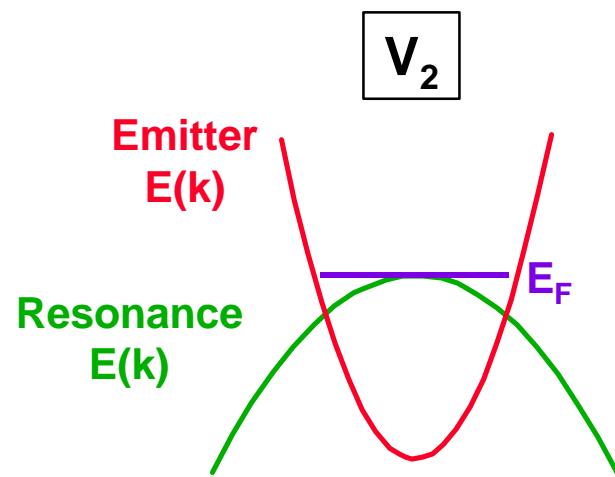
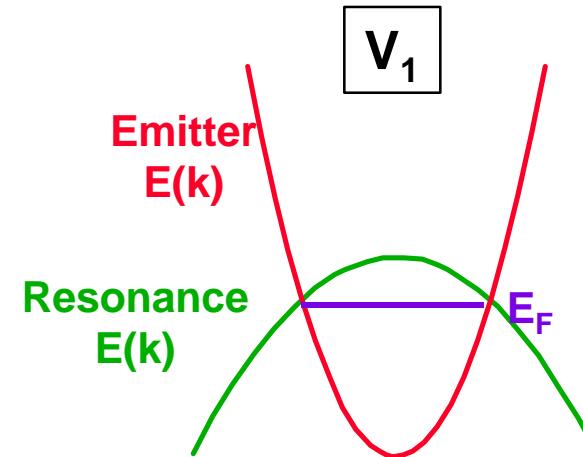
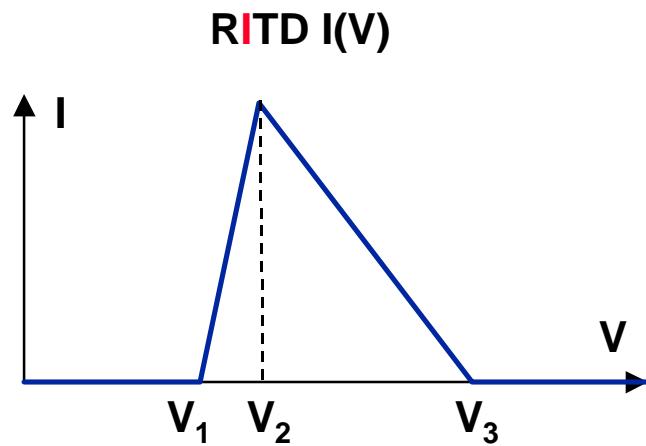
Type 1 RTD I(V) Basics ($T=0$)



Type 2 RITD Parabolic E vs k_{\parallel}



Type 2 RITD I(V) Basics (T=0)



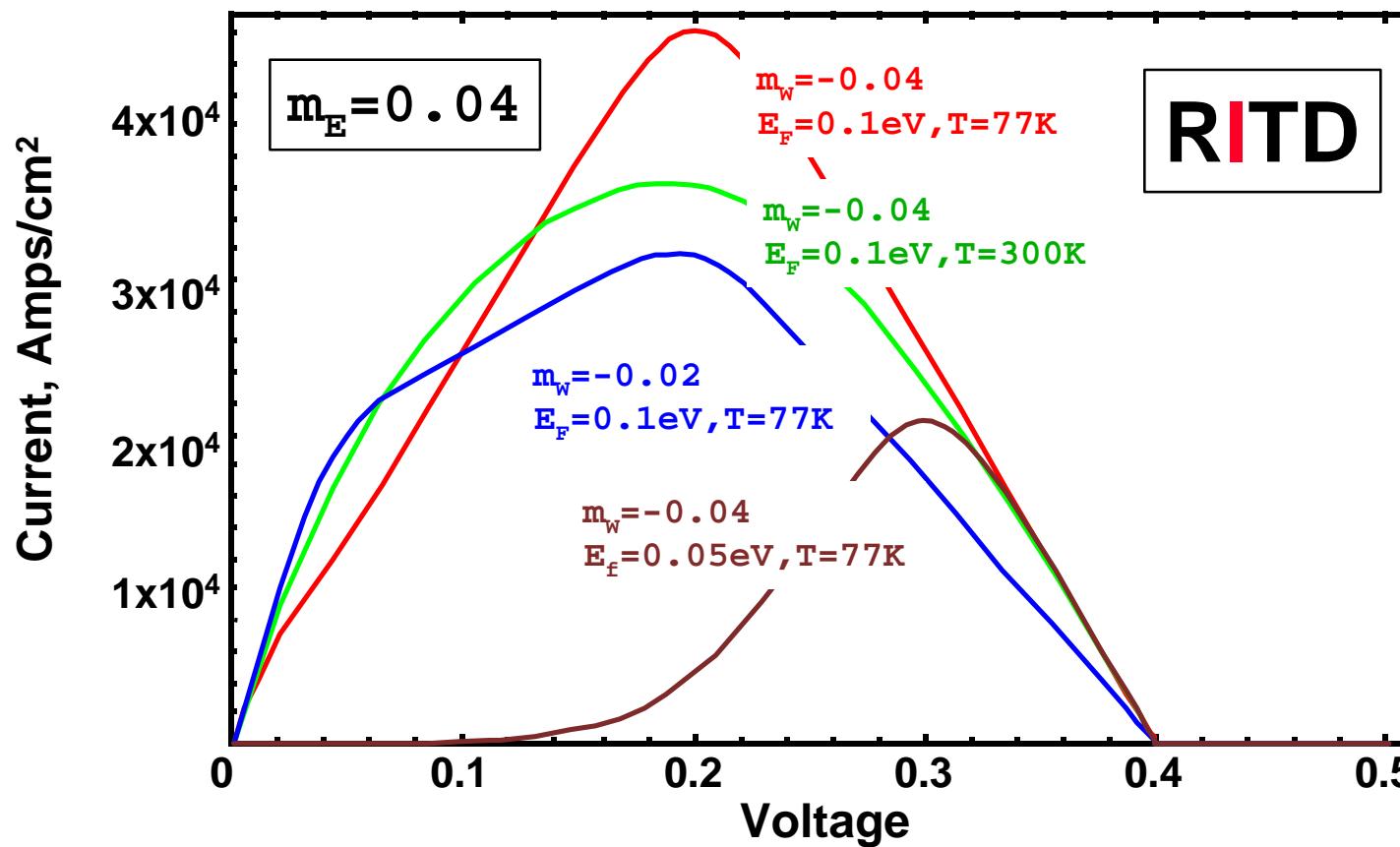
Comparison: RTD and RITD (T=0)

- Critical quantity: $\alpha = m_w / (m_w - m_E)$
 - m_E = emitter mass; m_w = mass of resonance in well
- RTD (Type 1): $\alpha > 1$ for $m_w > m_E$
 - $V_1 = 2 (E_R - E_F)$
 - $V_2 = 2 (E_R - E_F / \alpha)$
 - $V_3 = 2 E_R$
- RITD (Type 2): $\alpha < 1$ for $m_w < 0$
 - $V_1 = 2 (E_R - E_F / \alpha)$
 - $V_2 = 2 (E_R - E_F) \quad (E_R > E_F?)$
 - $V_3 = 2 E_R$
- ** RITD has *reduced peak voltage* for similar current density **
 - $V_2(\text{RTD}) - V_2(\text{RITD}) = 2 E_F m_E / |m_w|$
 - Collector band bending voltage reduced more than linearly

Extension of Tsu-Esaki Formula: $m_W \neq m_E$, $T > 0$

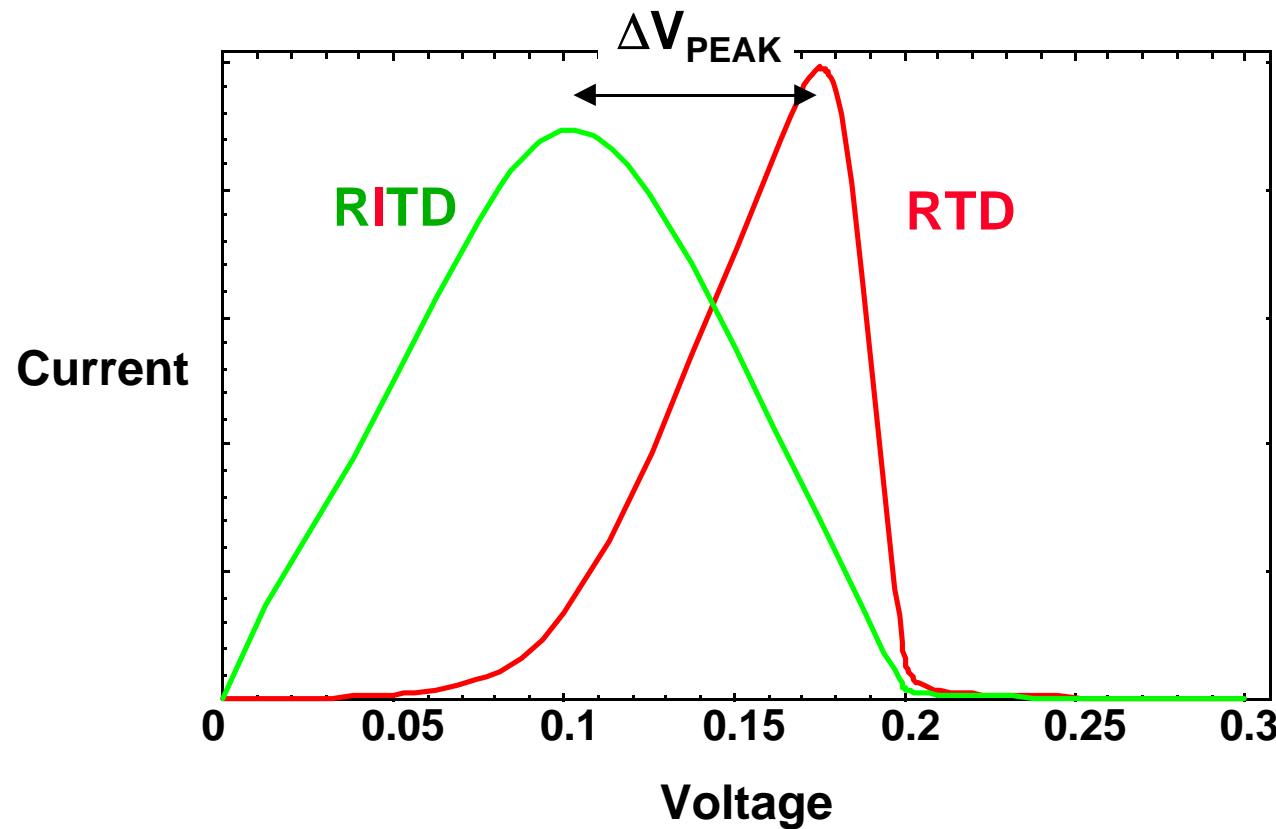
J.N. Schulman, Appl. Phys. Lett. 72, 2829 (1998)

$$J = \frac{m_W k T e}{2 p^2 \hbar^3} \int_0^\infty dU t(U) \log \left(\frac{1 + e^{(E_F - U)/kT}}{1 + e^{(E_F - U - eV)/kT}} \frac{1 + e^{(E_F - aU - eV)/kT}}{1 + e^{(E_F - aU)/kT}} \right)$$



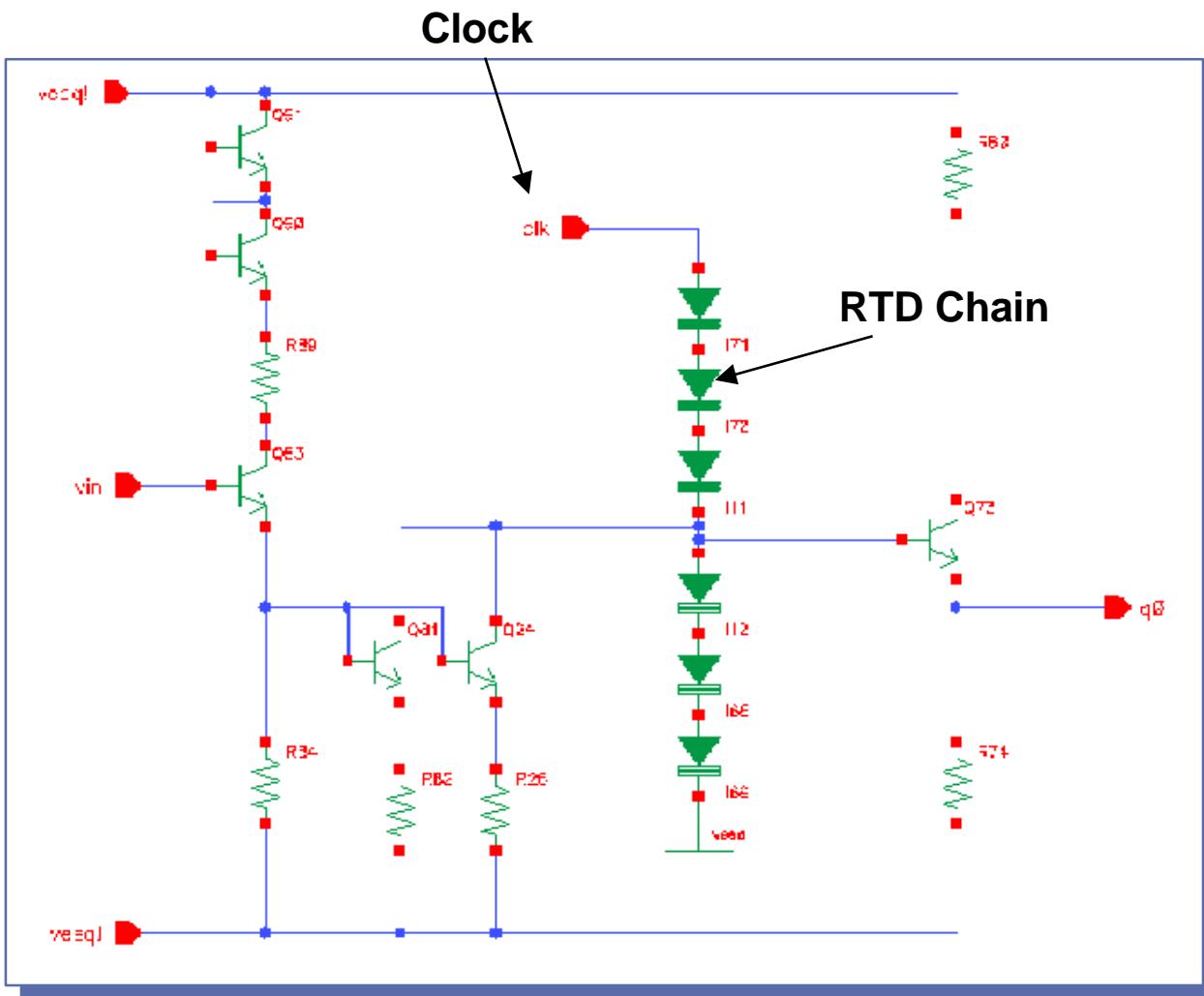
RTD, RITD I(V) Comparison

$m_E = 0.04, |m_W| = 0.05, T = 77 \text{ K}, E_F = 0.05, E_R = 0.1$



Multivalued Logic RTD Quantizer (based on NTT design)

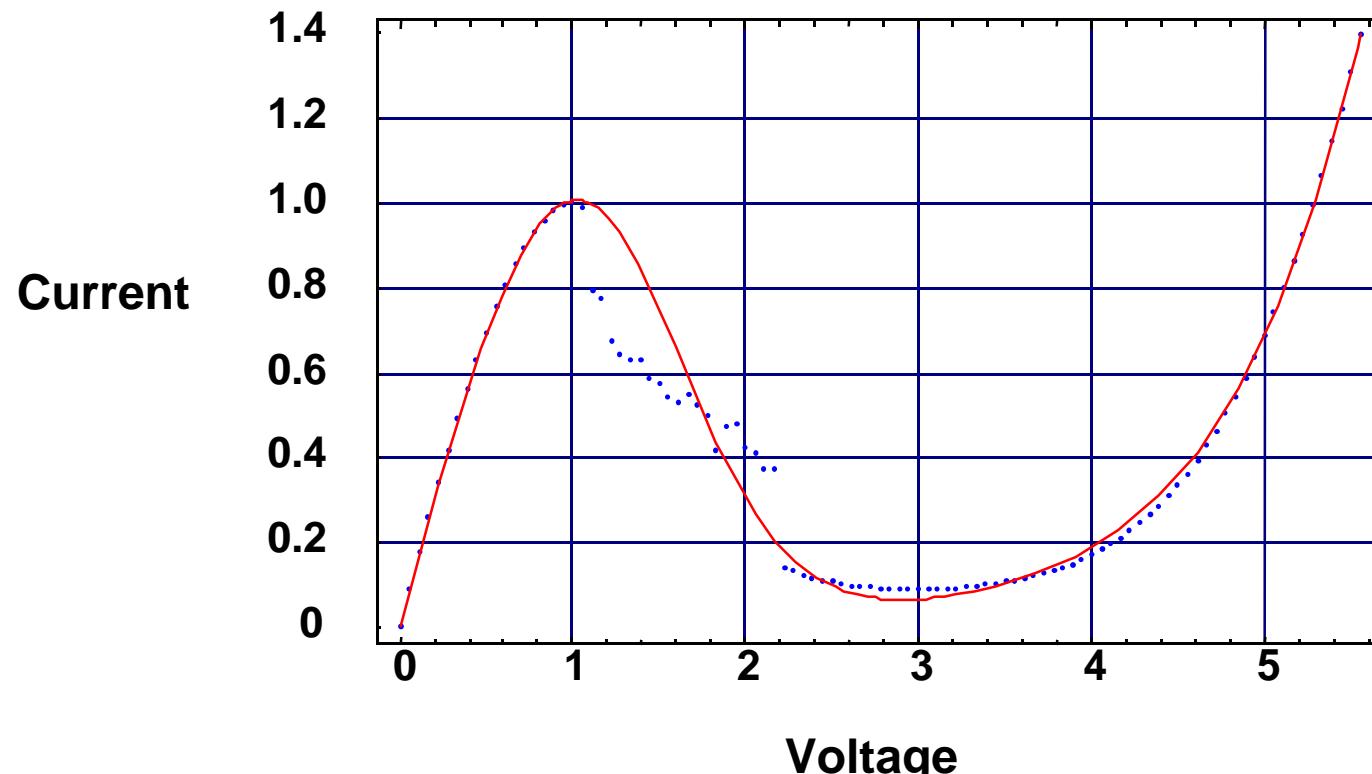
Clock Voltage ~ # of RTDs



SPICE-Compatible I(V) For RITD: *Data and Fit*

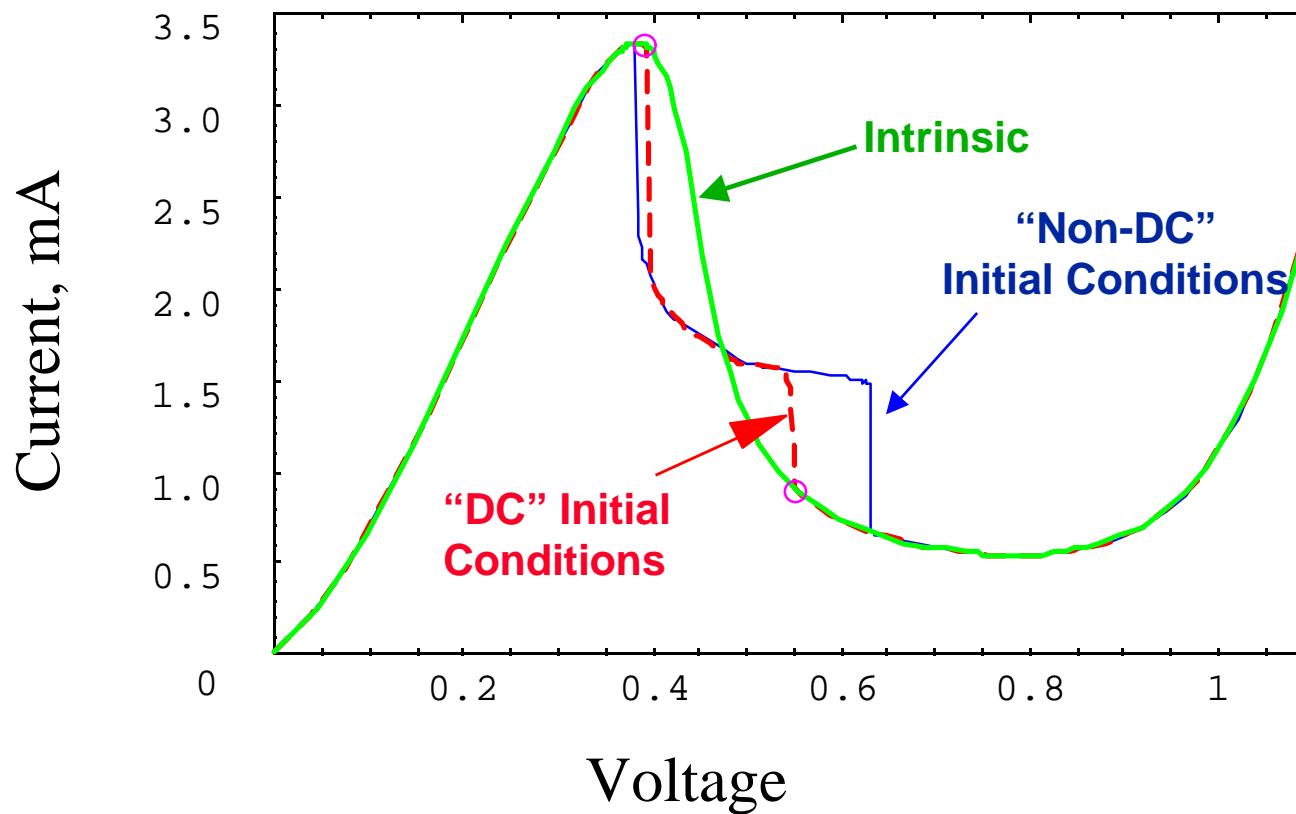
$$I(V) = -pa \operatorname{Log} \left(\frac{1 + e^{(b-c+n_1 V_s)/kT}}{1 + e^{(b-c-n_1 V_s)/kT}} \frac{1 + e^{(b-(c-n_1 V_s)\mathbf{b}-2n_1 V_s)/kT}}{1 + e^{(b-(c-n_1 V_s)\mathbf{b})/kT}} \right) + h(e^{n_2 V_s/kT} - 1)$$

$$V_s = V_0 - s \operatorname{Log}(1 + e^{-(V-V_0)/s})$$

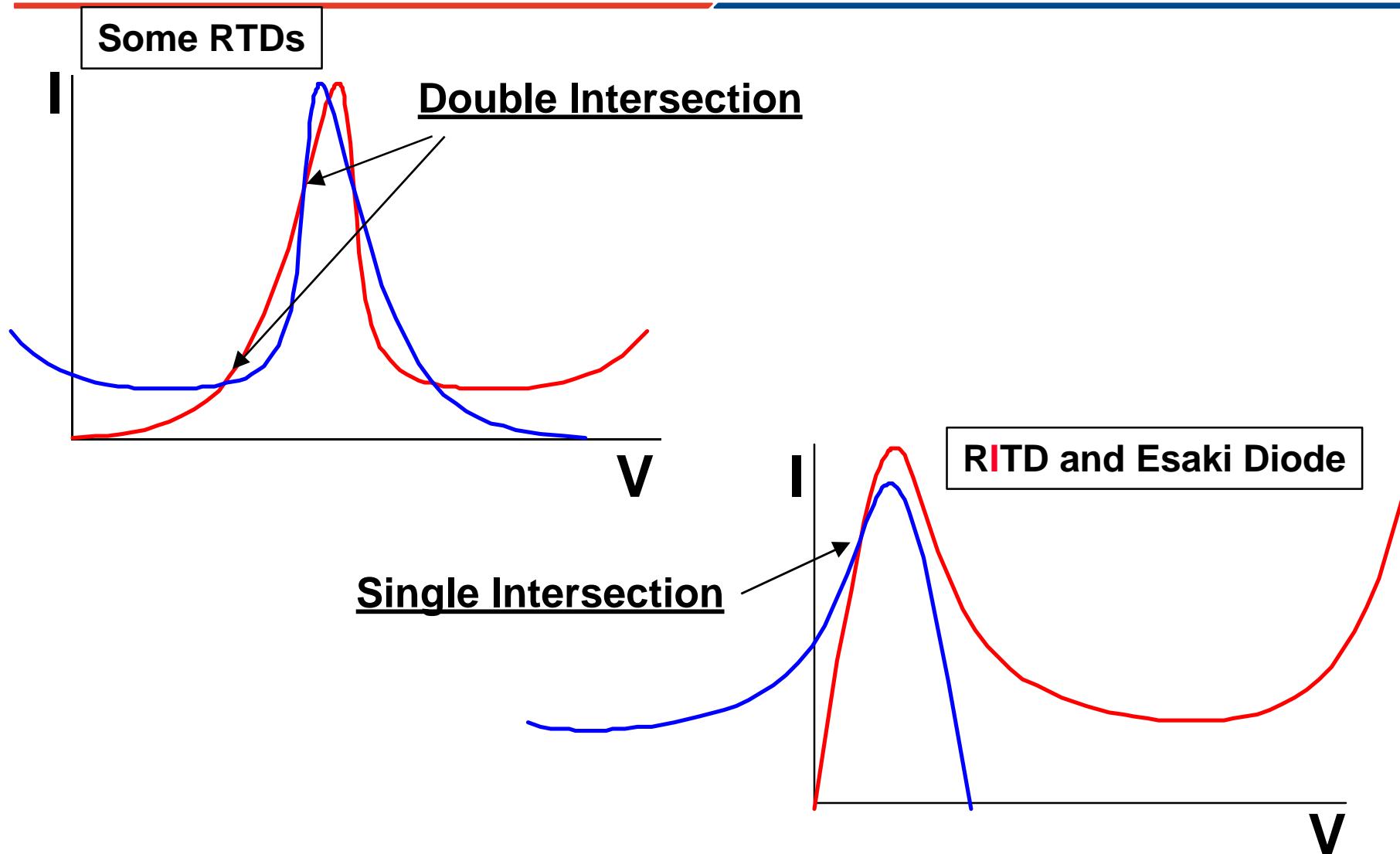


Measured vs Intrinsic I(V)

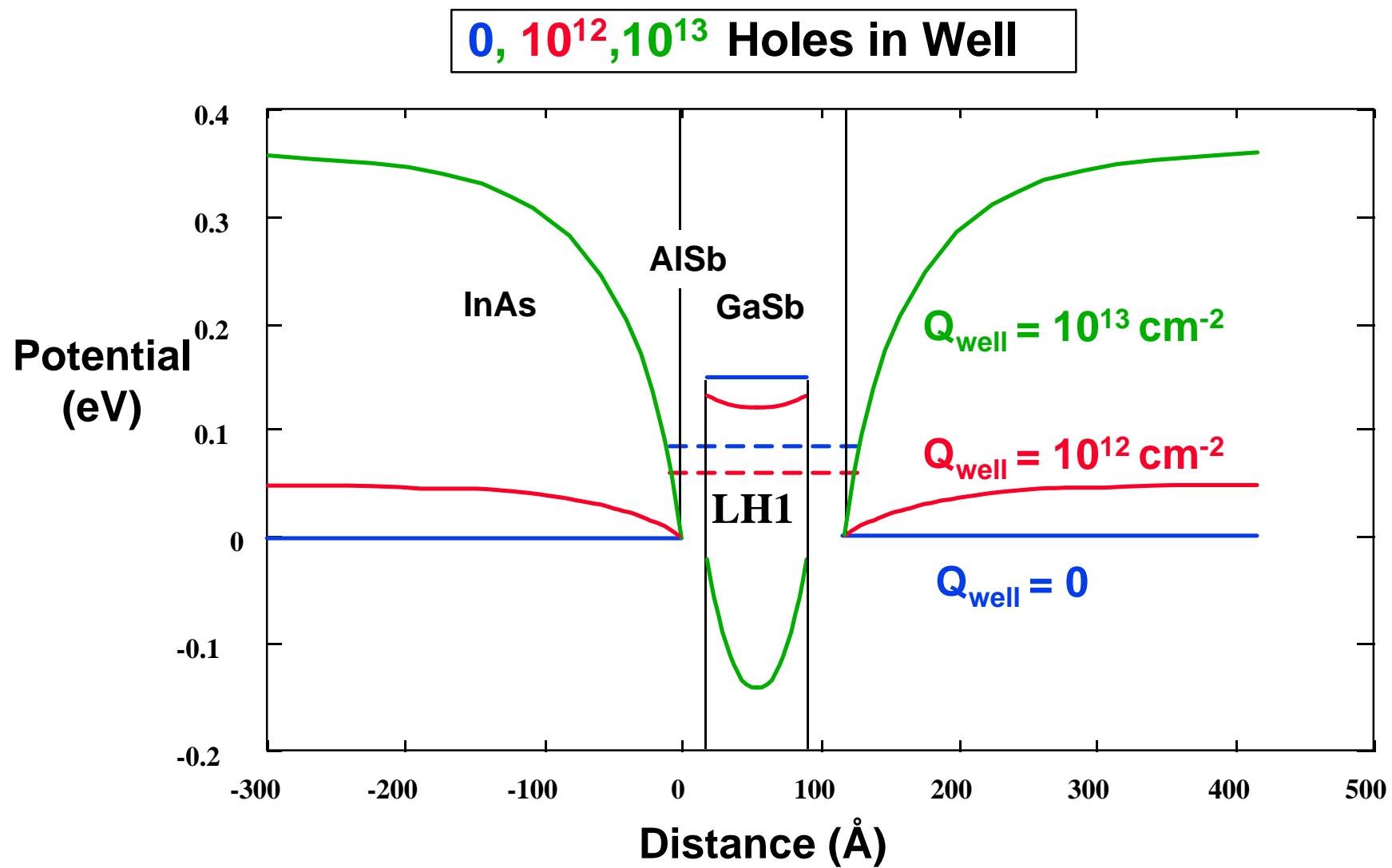
Measurement circuit induces I(V) sharpening



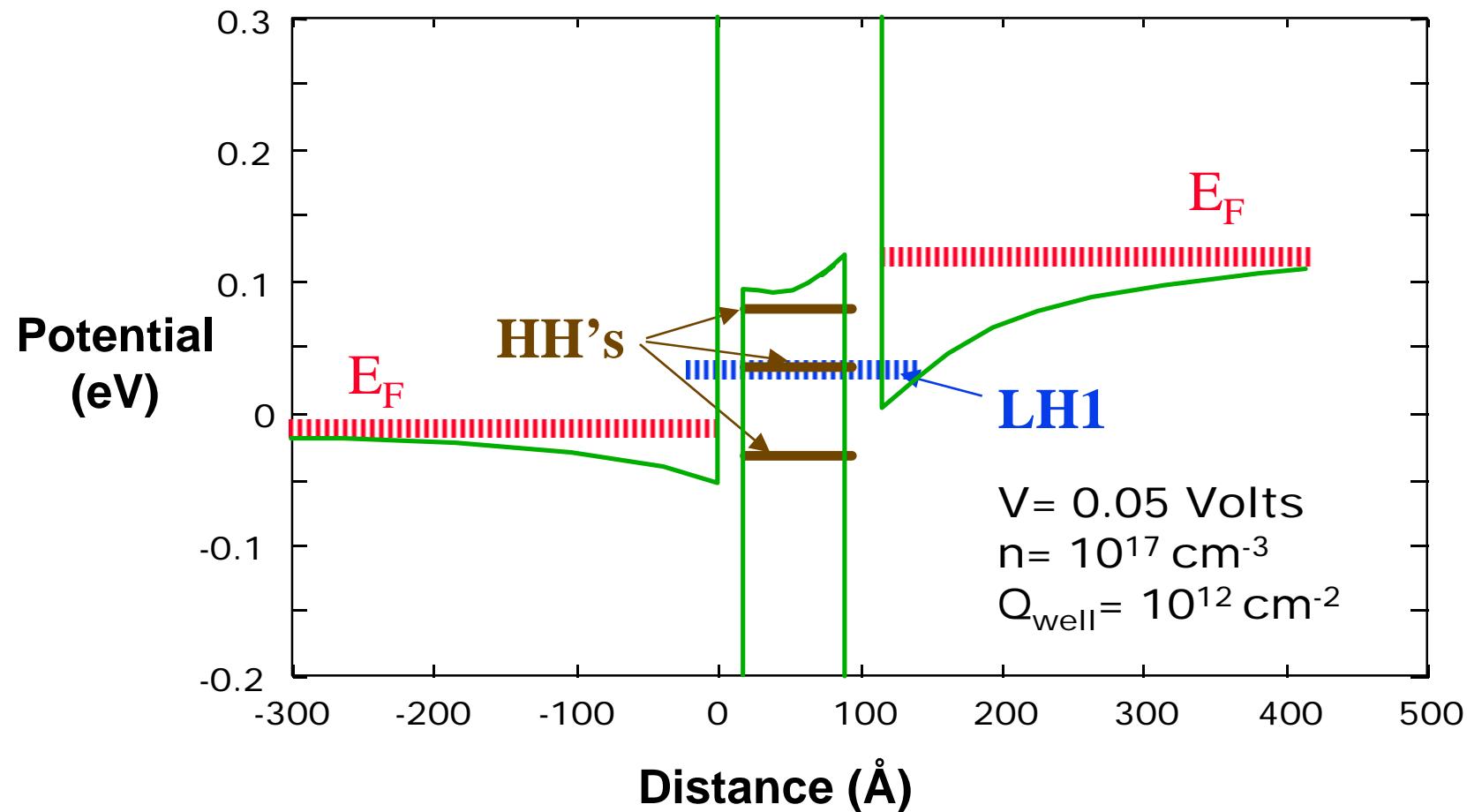
Balanced RTD Pair: Influence of Slopes



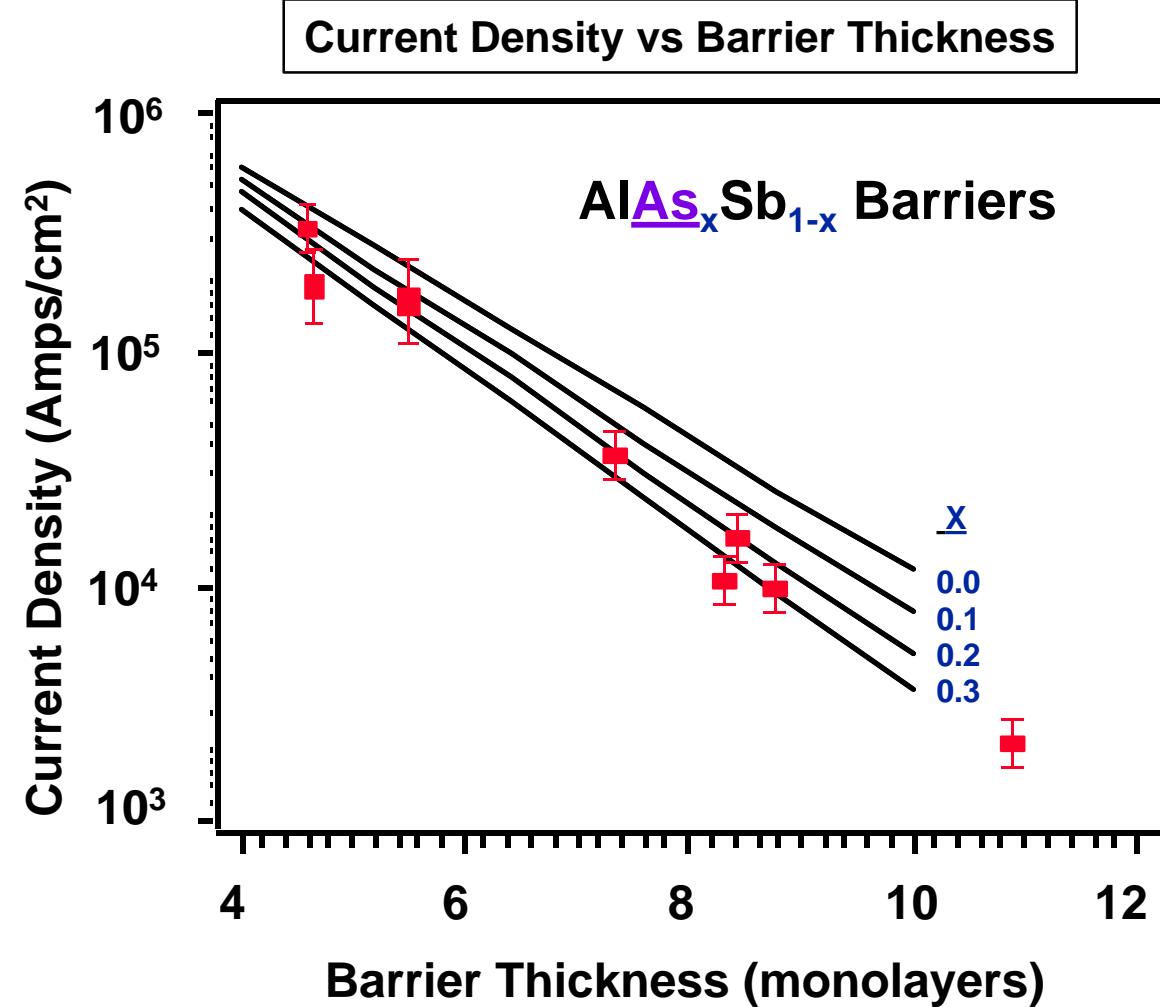
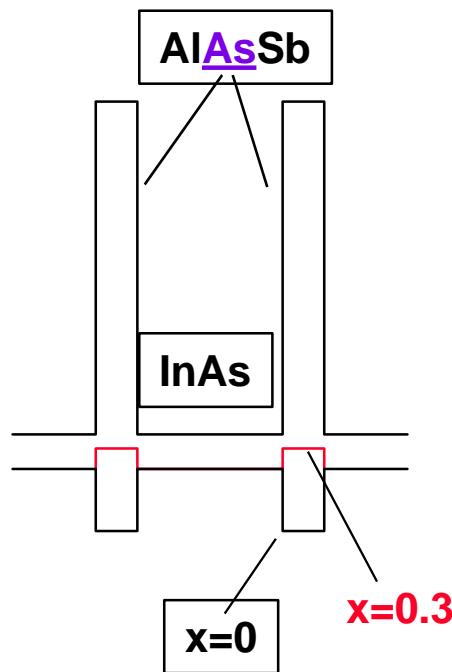
Effect of Confined Holes on RTD Band Profiles



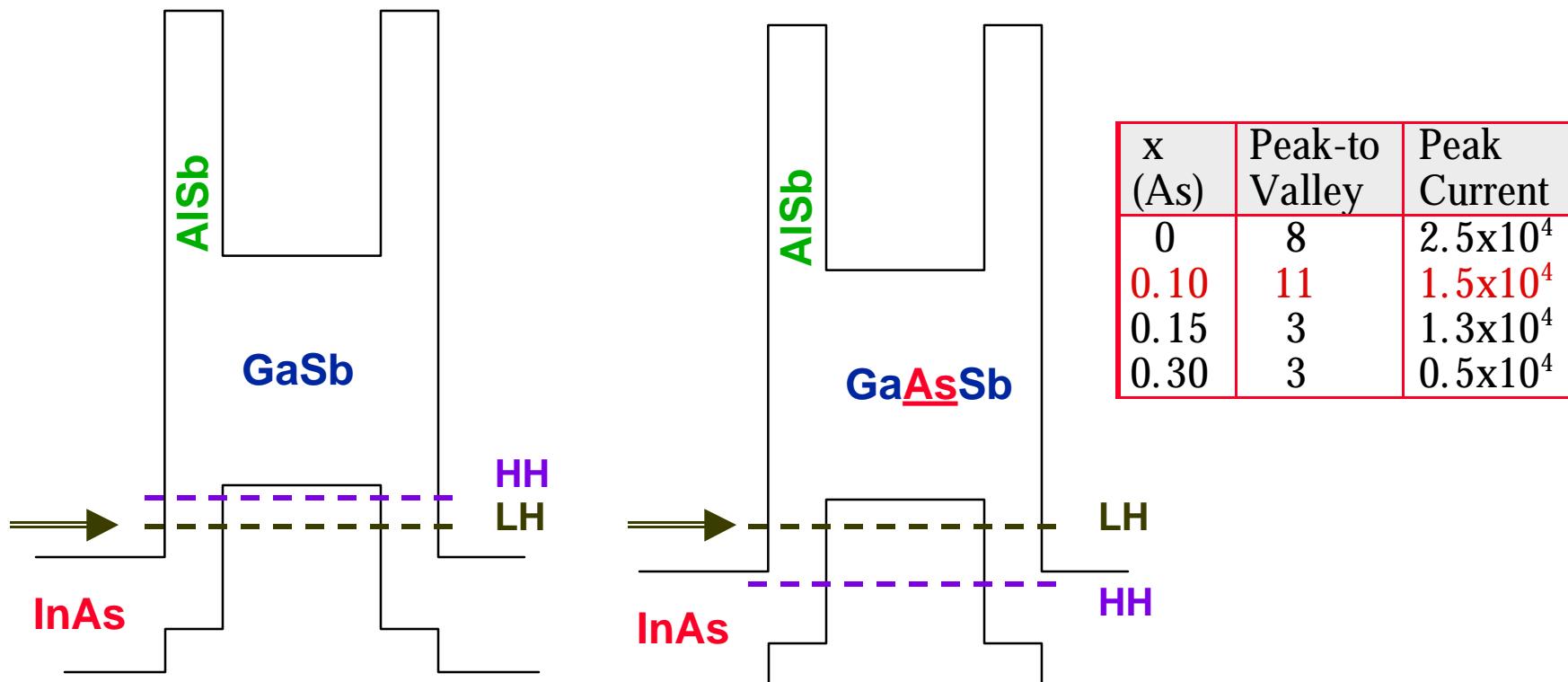
RITD Hole Confinement Effect, with Bias *Electric Field Screening*



Alloy Effect on Valence Band Discontinuity



Strain Shifted Heavy Hole: Eliminate Valley Current Channel?



Conclusions

- Basic I(V) curve characteristics understandable
 - Turn-on, Peak, Valley Voltages
 - Negative resistance
 - Effective masses, Fermi level important
- Interface roughness on I(V) should at least include $m_E \neq m_W$ effect
- Heavy/light hole mixing complicates calculation
 - Very difficult integration
 - Valence band structure not perfectly known and complicated
 - Charge accumulation
- Band offsets sensitive to alloy variations
 - Uncertain alloy concentration
 - Dependence on strain unknown and complicated
- Needed
 - More magneto-tunneling experiments
 - More modeling at all levels